Predicting Contaminant Removal Effectiveness of Three Air Distribution Systems by CFD Modeling

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ABSTRACT

This study compares the contaminant removal effectiveness (CRE) of three air distribution systems for a bar/restaurant setting by use of computational fluid dynamics (CFD) modeling. The air supply distribution and exhaust arrangement were modeled for a mixed air system, a directional air flow system (where air moves in a unidirectional flow pattern across the space, from the high-pressure supply area to the low-pressure exhaust area), and a displacement ventilation system (where supply air is delivered at low velocity close to the floor, allowing thermal plumes to be created). The CRE of each space was determined for both particulate and carbon monoxide dispersions under two different ventilation rates. A commercial CFD software package was used to model a hypothetical restaurant with bar in a steady-state condition with the inclusion of objects, such as a bar and multiple tables, heat sources such as people standing and seated, pollutant sources, multiple four-way supply air diffusers, and an exhaust air grille. The hospitality spaces' smoking and nonsmoking zones had no physical separation. The results demonstrated that directional airflow systems reduce nonsmokers' exposure to contaminants better than mixed air systems, and displacement ventilation systems reduce nonsmokers' exposure better than both directional airflow and mixed air systems.

INTRODUCTION

The purpose of any ventilation system is to provide a sufficient amount of outdoor air to remove contaminants and to maintain the interior environment at a comfortable temperature and relative humidity. The effectiveness of a ventilation system to perform these functions can be quantified in a number of ways e.g., air change efficiency of a system looks at air flow patterns only (Chow and Fung 1996; Nielsen 1993; Roos 1999), whereas contaminant removal effectiveness (CRE) quantifies the dilution and removal of a contaminant by a system. CRE is defined as the ratio between the steady-state concentration of the contaminant at the exhaust and the room or zone average value (Liddament 1993; Yaglou and Witheridge 1937).

The evaluation of CRE of three air systems was carried out using computational fluid dynamics (CFD) modeling. CFD modeling software has only recently become commercially available to heating, ventilating, and air-conditioning (HVAC) engineers in a package simple enough to learn and apply in a fairly short time. One virtue of CFD modeling is that it allows specific entry of details of the room that have relevance to the airflow. This feature is one that sets it apart from simple mass balance type models (Klepeis et al. 1996; Ott 1999) in which a room is largely described by its volume. CFD models have been used recently to study indoor air quality (IAQ) problems, pollutant dispersions, and performance of HVAC systems (Chow and Fung 1996; Emmerich 1997; Gadgil et al. 1999). Indoor environments studied using CFD modeling included offices (Reynolds and Hedge 1999), research laboratories (Memarzadeh 1999), an operating theater (Tinker and Roberts 1999), and an industrial workshop (Peng and Davidson 1998). Previous studies involving the evaluation or comparison of different air distribution systems have been published (Jiang et al. 1992; Holmberg et al. 1999; Kolokotroni et al. 1995; Yeoh and Li 1998). Ventilation plays an important role for reducing environmental tobacco smoke (ETS) in the design for smoking areas (ASHRAE 1981, 1989; Bohanon et al. 1998). The effect of ventilation on reducing ETS has been quantified in both laboratory studies (Cain et al.

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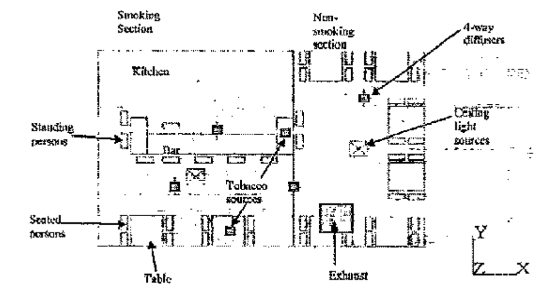
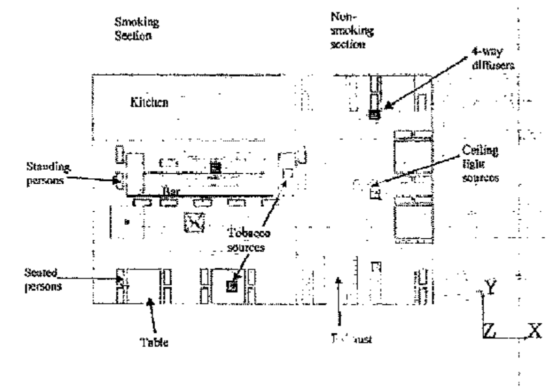
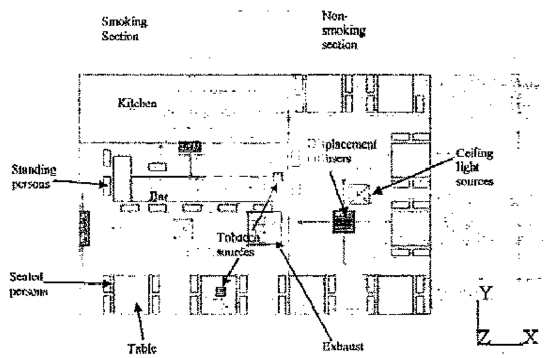


(a) Mixed Air



(b) Directional Airflow



(c) Displacement Ventilation

Figure 1 Room geometry in plan view.

1983; Cain et al. 1987; Enbom et al. 2000; Gunnarsen and Fanger 1991; Krühne and Fitzner 2000; Straub et al. 1993; Walker et al. 1997; Yaglou 1955) and some field studies (Bayer and Fischer 1997; Hedge et al. 1990; Hyvarinen et al. 1997). Most design guides principally rely on the ability of ventilation air to dilute ETS. In practice, ventilation may have a lesser effect, due to poor supply air distribution, or a greater one, if it is also used to establish pressure gradients that prevent smoke from entering nonsmoking areas or enhance the upward movement of smoke.

The objective of this study was to compare the performance of three air distribution systems according to their ability to remove contaminants, as estimated by their CRE (Enbom et al. 2000; Koganei et al. 1993; Liddament 1993; Roos 1999; Yaglou and Witheridge 1937). We quantified the effect of ventilation under well-defined conditions of source strength, supply and exhaust size and location, and space geometry. The CFD model used is an ideal tool because it allows for the variation of ventilation design as an independent variable across different alternatives. Such variation is expensive in the laboratory and infeasible for a field study.

In this study, a hypothetical hospitality space (a restaurant with a bar) was modeled with numerous airflow obstructions, heat sources, and tobacco smoke-generating sources placed within the smoking section. Two components of ETS were modeled: particulate and carbon monoxide (CO). The restaurant/bar was ventilated at two different airflow rates using three different air distribution systems, namely, a mixed air, a directional airflow, and a displacement ventilation system. The resulting distributions of the particulate and CO concentrations were then obtained and used for the derivation of the respective CRE values.

METHODS

Computational Fluid Dynamics Program

This study used a commercially available CFD program (Flomerics 1999) that could be readily applied by HVAC design engineers. This particular CFD program allowed a three-dimensional simulation to be carried out in a steady-state condition. The modeled space was divided into approximately 100,000 volume cells. The CFD program estimated variables such as pressure, velocity, temperature, and air constituent concentration for each cell, throughout the entire space in accordance with mass and concentration conservation equations.

The Model

The room modeled was 10 m long, 7 m wide, and 3 m high (Figure 1), consisting of a bar area (smoking area) and a restaurant area (nonsmoking area). The bar had nine people and one bartender standing around it. Each person generated approximately 100 watts of heat (ASHRAE 1997).

One tobacco smoke source was placed on the bar 0.3 m away from the nonsmoking area. This location was purposely selected to be close to the nonsmoking section to evaluate the potential movement of particulate and the gas phase component, CO, into the nonsmoking region. The other smoke source was placed on a tabletop closest to the non-smoking area. The use of two tobacco smoke sources in the model was based on the consideration of occupant loading of the space. It was assumed that each cigarette would last approximately eight minutes. Therefore, two cigarettes burning continuously were equivalent to fourteen cigarettes

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per hour. A particulate emission rate of 1 mg/min for each cigarette was chosen. This falls into a range of emission rates used by other studies (Klepeis et al. 1996; Miller-Leiden and Nazaroff 1996). Two 1 mg/min particulate sources would therefore generate 120 mg/h. Likewise, CO generation was modeled as 9 mg/min, which falls in a range identified by others (Klepeis et al. 1996; Jenkins et al. 2000).

In accordance with the ASHRAE ventilation rate procedure (ASHRAE 1999), a bar with 18 people would require 255.6 L/s of ventilation air, while the dining area with 23 people would require 216.2 L/s. As a result, the modeled space required a total outdoor ventilation rate of 472 L/s.

To investigate the effect of reduced ventilation on the CRE of the three air distribution systems, simulations were also carried out with 50% of the required ASHRAE ventilation rate, i.e., 236 L/s.

Each tobacco source was modeled as 6 watts of heat (Waymack et al. 1997). This heat made the particulate and CO buoyant at the source. The diffusion coefficient used for CO was 2×10^{-5} m^2/s (Lundgren et al. 1979) and 2×10^{-10} m^2/s (Lide et al. 1969) for the particulate, since these particles are 0.2 micron in diameter (Jenkins et al. 2000).

The exhaust grille was the location used to determine the whole space mean concentration for all cases modeled. In a steady-state solution, all the mass flows into the space must equal all the mass flows exiting the space, which occurs at the exhaust grille. Therefore, the contaminant concentration in the exhaust air grille for the mixed air spaces, the directional airflow spaces, and the displacement ventilation systems was a constant (Tables 2 and 3) under the same ventilation rate.

The spaces that were designed for mixed air and directional airflow had ceiling-mounted four-way diffusers (Figures 1a, 1b). The air was delivered into the room at 14°C with zero particulate and CO levels. This supply air was more dense than the room air; therefore, it dropped downward toward the floor due to gravity. There was one four-way diffuser located above the bar. It delivered 47.2 L/s, while each of three other ceiling diffusers delivered 141.6 L/s of ventilation air (a total of 472 L/s). Thus, each diffuser generated a primary air jet, which in turn set up multiple secondary air jets within the space. For the mixed air geometry, the supply air diffusers were located across the ceiling on both sides of the space. For the directional air flow geometry, 90% of the supply air moved from the nonsmoking side of the space into the smoking side.

In the case of the displacement ventilation space, all the air was delivered to the space with floor-mounted diffusers at low velocity (less than 0.1 m/s). All three cases modeled had their own unique airflow patterns, due to the heat sources and obstructions in each space.

The CRE was determined by solving for the contaminant concentration in the exhaust grille divided by the mean concentration in the breathing zone of the nonsmoking region (Figures 1a, 1b, and 1c). The face of a seated or standing person (between 1.2 m to 1.9 m elevation) in this nonsmoking section would be located within this specific region.

$$CRE = \frac{C_E - C_S}{C_{BZ} - C_S} \tag{1}$$

where CRE = contaminant removal effectiveness; C_E = mean concentration in exhaust; C_S = mean concentration in supply air; C_{BZ} = mean concentration in occupied breathing zone.

RESULTS AND DISCUSSION

Mixed Air Systems

The purpose of all mixed air systems is to create enough room air turbulence such that a uniform temperature and contaminant concentration exists. The CRE values (particulate and CO) of the modeled restaurant/bar with the mixed air system at both ventilation rates were in a narrow range from 1.0 to 1.2 (Table 1). The contaminant concentration was found to be typically within 15% of that at the exhaust grille (Table 2). The higher ventilation rate resulted in a reduced nonsmoker exposure to contaminants in mixed air systems due to dilution. Both particulate matter and CO are distributed similarly throughout the space, as is demonstrated by the CRE values. Both of these substances, although different in diffusion coefficient, moved as a result of the prevalent air currents within the space.

The hospitality space was modeled with clean supply air. This was done to simplify the comparisons in the figures. Supply air is rarely found to be particulate free. However, as observed from formula 1, a contaminant in the supply air is subtracted out from both the numerator and denominator and results in the same CRE being determined as if it was clean supply air.

Figures 2a and 3a display the concentration contour results for the mixed air systems at 472 L/s ventilation air. Figure 4a displays the particulate concentration contours for the lower ventilation rate. The concentration contours are shown as a plan cut through each space at 1.7 m elevation. The mixed air systems consistently (Table 1) exhibit the lowest CRE values in all cases. At the lower ventilation situation (Table 3) an uncomfortably high exhaust temperature (31°C) and higher contaminant concentrations were found. Also at the lower ventilation rate, less mixing took place within the space, resulting in CRE values slightly higher than those found at the higher ventilation rate.

Directional Airflow

The purpose of directional airflow systems is to supply clean air into the nonsmoking section and direct its movement into the smoking section in order to minimize the presence of smoke in the nonsmoking section. The CRE values (particulate and CO) of the modeled restaurant/bar with the directional airflow system at both ventilation rates were consistently higher (Table 1) than the mixed air cases, indicating that contaminant concentrations in these nonsmoking regions were lower than those found when the mixed air systems were in use.

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TABLE 1
Contaminant Removal Effectiveness (CRE) Summary

Ventilation Rate		Mixed Air	Directional Airflow	Displacement Ventilation
472 L/s	Particulate	1.1	2.7	17.5
	CO	1.0	2.6	15.8
236 L/s	Particulate	1.2	1.4	7.4
	CO	1.2	1.4	8.1

TABLE 2
472 L/s Ventilation Rate

Parameters (unit of measure)	Mixed Air	Directional Airflow	Displacement Ventilation
Total supply airflow, L/s	472	472	472
Supply air particulate concentration, μg/m^3	0	0	0
Supply air temperature, °C	14	14	16
Exhaust flow, L/s	**472**	**472**	**472**
Exhaust temperature, °C	23	23	25
Particle concentration exhaust, μg/m^3	**70**	**70**	**70**
Particle concentration nonsmoking region, μg/m^3	**63**	**26**	**4**
Particulate contaminant removal effectiveness (CRE)	**1.1**	**2.7**	**17.5**
CO concentration exhaust, μg/m^3 (ppm)	**631 (0.6)**	**629 (0.6)**	**631 (0.6)**
CO concentration nonsmoking region, μg/m^3 (ppm)	**624 (0.6)**	**243 (0.2)**	**40 (0.0)**
CO contaminant removal effectiveness (CRE)	**1.0**	**2.6**	**15.8**

Note: Bold indicates calculated results from input data.

TABLE 3
236 L/s Ventilation Rate

Parameters (unit of measure)	Mixed Air	Directional Airflow	Displacement Ventilation
Total supply airflow, L/s	236	236	236
Supply air particulate concentration, μg/m^3	0	0	0
Supply air temperature, °C	14	14	14
Exhaust flow, L/s	**236**	**236**	**236**
Exhaust temperature, °C	31	31	31
Particle concentration exhaust, μg/m^3	**140**	**141**	**140**
Particle concentration nonsmoking region, μg/m^3	**120**	**98**	**19**
Particulate contaminant removal effectiveness (CRE)	**1.2**	**1.4**	**7.4**
CO concentration exhaust, μg/m^3 (ppm)	**1274 (1.1)**	**1268 (1.1)**	**1269 (1.1)**
CO concentration nonsmoking region, μg/m^3 (ppm)	**1081 (0.9)**	**878 (0.8)**	**157 (0.1)**
CO contaminant removal effectiveness (CRE)	**1.2**	**1.4**	**8.1**

Note: Bold indicates calculated results from input data.

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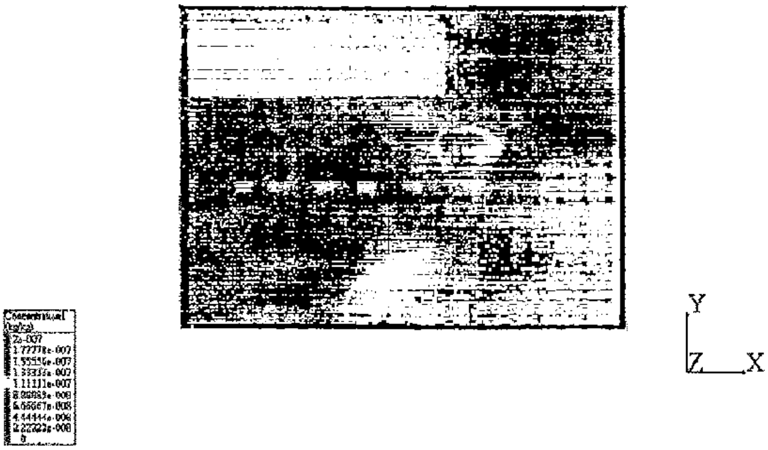
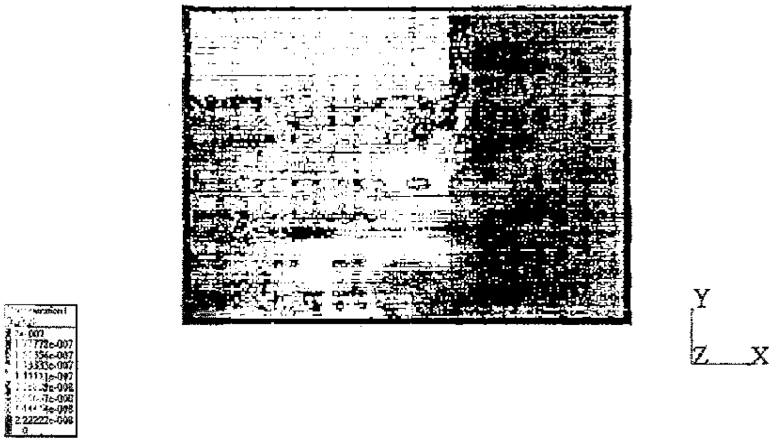
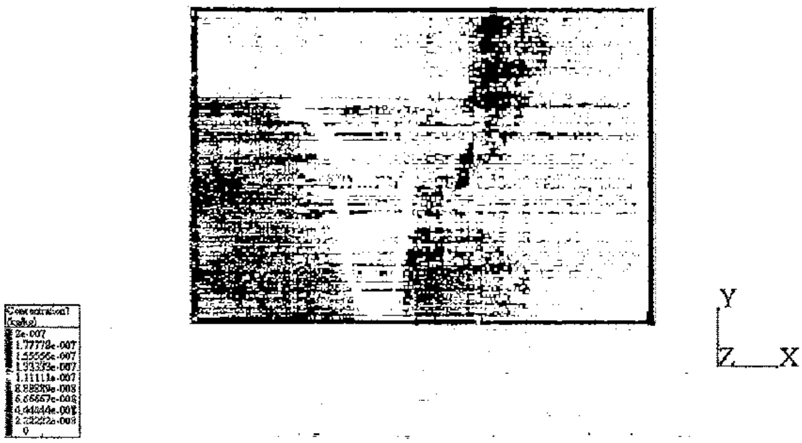


(a) Mixed Air



(b) Directional Airflow



(c) Displacement Ventilation

Figure 2 Particulate concentration fills at 1.7 m above floor, 472 L/s ventilation rate.

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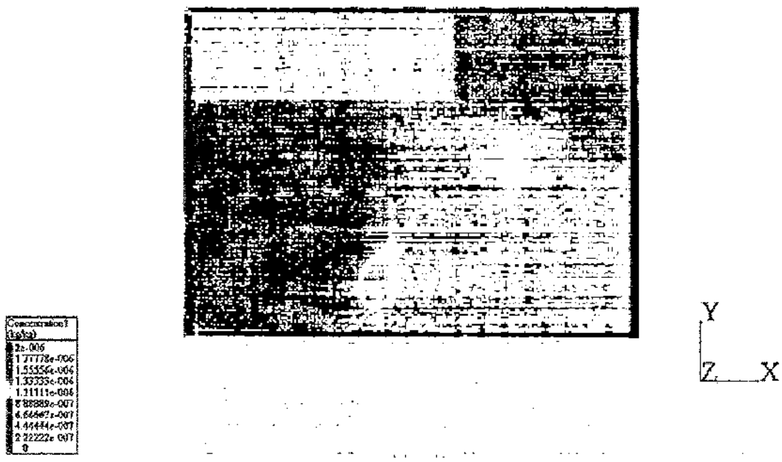
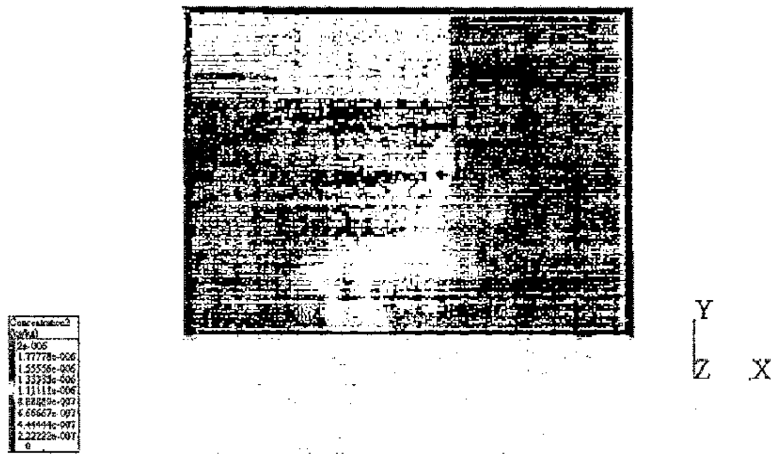
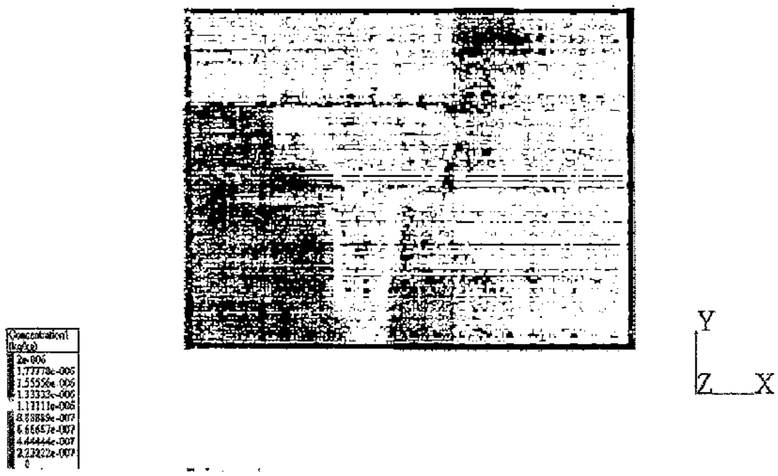


(a) Mixed Air



(b) Directional Airflow



(c) Displacement Ventilation

Figure 3 *CO concentration fills at 1.7 m above floor, 472 L/s ventilation rate.*

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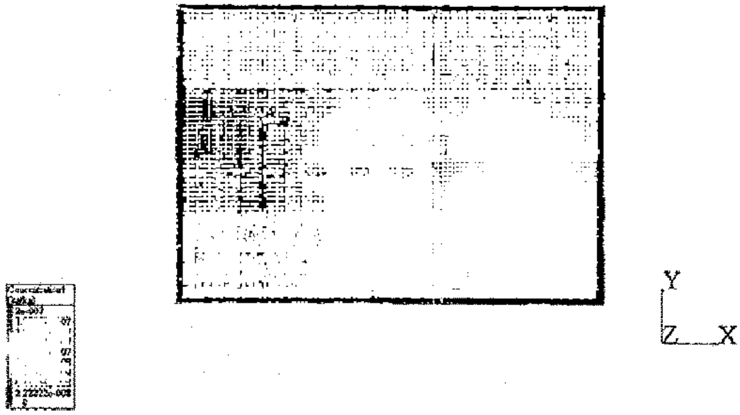
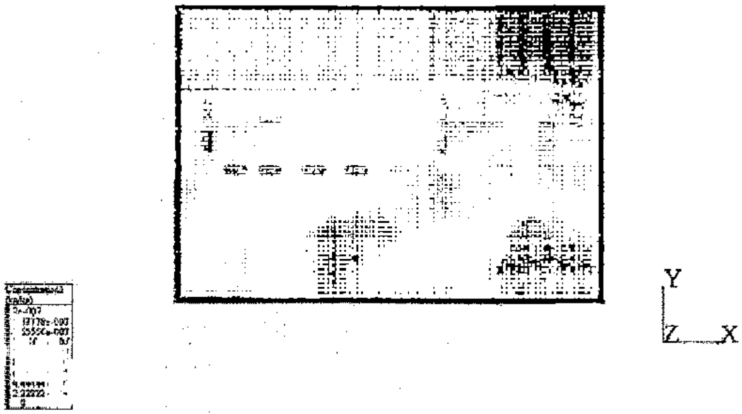
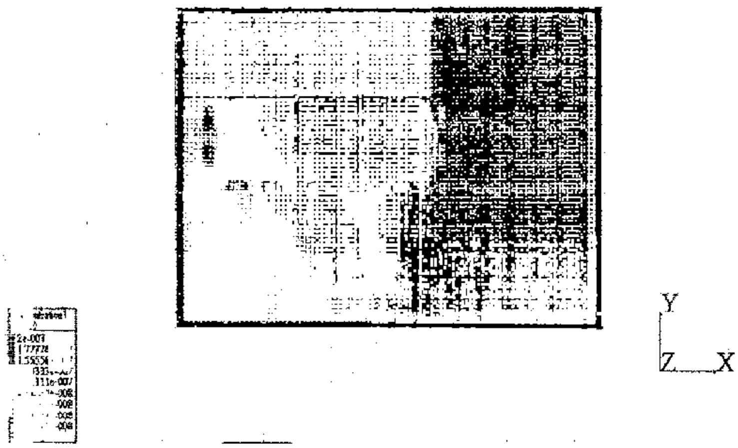


(a) Mixed Air



(b) Directional Airflow



(c) Displacement Ventilation

Figure 4 Particulate concentration fills at 1.7 m above floor, 236 L/s ventilation rate.

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The CRE values for directional airflow systems were 1.4 at the lower ventilation rate and 2.7 at the higher ventilation rate. At the lower ventilation rate, the spaces had insufficient airflow to adequately control the diffusion of the contaminants from the smoking area into the nonsmoking area. Figures 2b and 3b display the concentration contours at the 472 L/s ventilation rate, while Figure 4b shows the particulate concentration contours for the lower supply air case.

Displacement Ventilation

The purpose of displacement ventilation is to introduce cool supply air into the space at low velocities, thus minimizing any air turbulence or mixing within the space. The air was supplied close to the floor and therefore pooled along the floor. Air then flowed vertically upward around all heat sources. Contaminants from tobacco sources were heated in the combustion process and their natural tendency to rise as buoyant particles was enhanced by the vertical airflow pattern in displacement ventilation spaces.

The dispersion of contaminants into the nonsmoking area was found to be minimal with the use of displacement ventilation. The highest CRE values (particulate and CO) resulted from displacement ventilation systems and were 7.4 at the lower ventilation rate and 17.5 at the higher ventilation rate (Table 1). Even operating at the lower ventilation rate, the displacement ventilation system provided nonsmoking area exposure levels that were lower than either the mixed air or directional airflow system operating at their higher ventilation rate. Figures 2c, 3c, and 4c illustrate the typical concentration contours for this air distribution system at the 1.7 m elevation in the space. It can be observed that the spread of the particulate and CO within the model was very similar at the two ventilation rates.

Movement of people in a space with displacement ventilation may reduce the CRE value, since some air turbulence is created (Brohus and Nielsen 1994). It is not expected to change the relative differences in contaminant removal effectiveness for the three ventilation systems. A recent test room study where the effectiveness of mixing ventilation system arrangements was compared to displacement ventilation system arrangements using a smoking/nonsmoking zone setup seems to confirm our findings (Enbom et al 2000). Enbom's study found that some displacement system configurations would reduce nonsmokers' exposure by 98% when compared with the situation of complete mixing. In our case, we calculate from Table 2 (4/63 x100) a reduction of 94%.

CONCLUSIONS

CFD modeling can be a useful tool to evaluate HVAC designs of spaces before they are built. It allows engineers to view air movement, room temperature, and concentration of contaminants within a space and to perform analyses of the impact of design changes.

The vast majority of all spaces employ the mixed air arrangement. This study demonstrated that the other HVAC arrangements modeled, i.e., directional airflow and displacement ventilation, may be alternatives for designing hospitality spaces where smoking occurs. In all cases modeled, the displacement ventilation system consistently had the highest CRE values (Table 1) and the directional airflow design consistently ranked above all mixed air systems.

The directional airflow systems modeled showed CRE values more than twice as high as the mixed air systems at the higher ventilation rate. If a sufficient quantity of air is moving in one direction across the space, then contaminants generated in the smoking side of the space will be pushed toward the exhaust. The CRE of directional airflow systems is highly dependent upon the total airflow moving from the nonsmoking area into the smoking area. Higher airflow is expected to produce higher CREs, while at too low a flow, a result more like mixing should occur. Displacement ventilation performed best at directing contaminants to the upper regions of the space and was not as dependent upon total supply airflow as the mixed air and directional airflow systems were.

Both particulate and gas phase movement were modeled with their different diffusion coefficients. There were small differences in the overall results between these substances as both contaminants moved in the direction of the prevalent air current.

Using CRE is a straightforward method for determining and comparing how effective any ventilation system is in removing contaminants, or providing a partitioning effect within the space. This method should become a valuable IAQ measure in the future, as it is easy to calculate for any real space. This study demonstrated that ventilation rates affect the contaminant levels within a space, but significant improvements in minimizing concentration of smoke in nonsmoking areas can also be achieved by switching to either a directional airflow or displacement ventilation system.

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